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OCCULTATIONS: THEIR PREDICTION, OBSERVATION AND REDUCTION

By H. BOYD BRYDON

INTRODUCTION

"Except ye utter words easy to be understood, how shall it be known what is spoken?"—I Cor. XIV 9.

THE prediction, observation and reduction of occultations rank high among the interesting, useful and important activities available to the amateur astronomer, no matter how small his experience or modest his equipment. Interesting, because the sudden eclipse of a star by the dark, nearly invisible limb of the moon and its equally sudden reappearance offer one of the thrills of observing; useful, because, when carefully made, such observations afford data for refining lunar theory, thereby increasing the accuracy of our nautical almanacs; important, because, although a multitude of observations is necessary for that purpose, very few occultations are visible during the course of a year from any one place and it is only by combining observations from many places that the accidental errors due to the mountainous character of the moon's limb can be eliminated. Careful observation and recording of the details of an occultation moreover may serve to throw light on the subject of irregular refraction and on some problems regarding the physical condition of the moon.

Idle star-gazing soon ceases to interest. Only as in some way it serves one's fellow man can a hobby live. Occultations of stars by the moon offer to the amateur astronomer a signal opportunity to put his hobby to use in the service of science. His reward is the lasting satisfaction that results from work faithfully done.

For most of us whose days have to be spent in minding our own business, for which the first four rules of arithmetic generally suffice, interest in occultations is apt to be quenched by the formulae, trigonometric and logarithmic, that confront us when we seek information on the subject. In most works on practical astronomy the reader is assumed to possess knowledge which, though part of the preliminary training of the professional astronomer, is foreign to the life-work of his amateur brother. As it is the purpose of this paper to rekindle that interest and bring it to the glow of steady accomplishment, be it said to anyone thinking to forego this branch of astronomy because of unfamiliarity with sines and tangents, cosines and logarithms, that these are but the names of common things, just as "dodecahedron" is the shape of the new five-cent piece and "parallelepiped" is the shape of a shoe-box or of the room in which these words are being read.

All the trigonometry needed is contained in tables, the use of which, like the use of a table of logarithms or of a slide rule, can be learned literally in a few minutes by anyone familiar with those first four rules for "full directions are enclosed."

PARALLAX. Parallax (the word is Greek and means "to make things change position") enters into many problems relating to occultations. Observers at points A and B, on the earth E, Fig. 1, see a neighbouring celestial body such as the moon in different directions. That their observations may be compared, they must be "cleared of parallax" by reducing them to the values they would have if made from a common point, namely, the centre E of the earth. The change in the direction of the body as seen from the observer's position and from the centre of the earth is "the parallax" of the body at the time and place of the observation.

In Fig. 1, let A and B be the positions of two observers on the earth's surface; then the angles α and β are the corresponding zenith distances of the object M (here the centre of the moon). If α and β be compared it will be seen that the farther a heavenly body is from the observer's zenith Z, the greater is its change in direction as seen from A and from E, and the greater is the "correction for parallax." Hence, when the body is seen on the horizon, as is the case at A; that is, when it is rising or setting; its parallax is greatest and is known as its "horizontal parallax." Finally,

because the radius of the earth is greatest at the equator, the greatest horizontal parallax occurs when the body is seen on the horizon by an observer on the equator. This is its "equatorial horizontal parallax" and is "the parallax" of the sun, the moon, or a planet as given in the text-books.

The parallax of a star, or "stellar parallax," is a similar concept but is based upon the semi-major axis of the earth's orbit round the sun and does not concern us here.

Instead of describing the parallax of a body as the difference between its directions as seen from the centre of the earth and from the end of an equatorial diameter, it is often convenient in

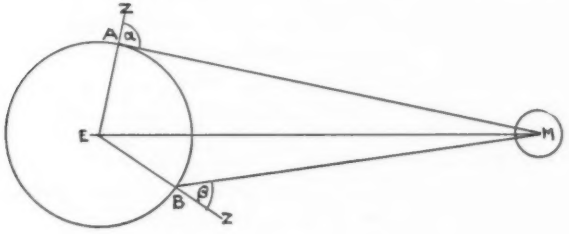

Fig. 1.—Parallax of a body.

practice to define it as the angle subtended at the centre of the heavenly body by the line joining those two points; or, in more formal language, "parallax of a heavenly body is the angle subtended at the centre of that body by the earth's equatorial radius."

Let us consider next an effect, important in occultation work, which is caused by the diurnal rotation of the earth. The axis of the earth when produced cuts the celestial sphere in the north and south celestial poles, and great circles running between these poles are called hour circles. The N-S direction at any point in the sky is along the hour circles passing through that point.

Suppose now the moon is rising at the east horizon. The hour circle passing through the centre of the moon cuts the limb of the moon in two points. That one towards the north celestial pole is the *north point* of the moon's limb—a very important point in dealing with occultations. Denote it by *n*. Also consider the

vertical circle passing through the centre of the moon. As it runs upward to the zenith it cuts the moon's limb at its top point, and that point is defined to be the *moon's vertex*. Denote it by v. To an observer facing the east, v is to the right of n, and the arc of the limb between n and v has a certain value, say x degrees.

As the moon rises this arc diminishes or x gets smaller until when the moon is on the meridian $x = 0°$ and v coincides with n. As the moon moves onward, v separates from n to the left as seen by the observer facing west. It continues to separate until the moon reaches the western horizon when the arc between the vertex and the north point has the same value as at the eastern horizon.

While descriptions and figures in this paper apply directly for places in the northern hemisphere, they serve equally well in the southern by reversing north and south and east and west, both in the text and in the diagrams.

Lastly, a word of explanation. In some of the formulæ in this paper Greek letters are used. This is done simply because they are the accepted symbols for the ideas they represent. Acquaintance with them removes a fruitful source of difficulty when reading advanced text-books.

This is a suitable occasion to acknowledge valuable assistance received by the author. My thanks are offered to the Astronomer Royal, Sir H. Spencer Jones, for words of encouragement and for permission to make quotations from the *Nautical Almanac*; to Dr. C. H. Gingrich for permission to quote from *Popular Astronomy*; to Mrs. Isabel M. Lewis and Mr. L. S. Barnes for permission to quote from their notable papers on occultations; and to Dr. J. A. Pearce, Dr. R. M. Petrie and Dr. Alice H. Farnsworth, who have generously taken the time to read the manuscript or proof and by their comments have done the author and his readers an inestimable service.

Method of Prediction

The occurrence and the circumstances of an occultation can be predicted either graphically or mathematically. The advantage is emphatically with the graphic method. As Mrs. Lewis points out:[1]

[1]Isabel M. Lewis: The Selection and Prediction of Occultations for any Place and Time; *Pop. Ast.*, vol. 43, 1935.

"The graphic method quickly eliminates those cases for which impossible results would be obtained by the analytical method after carrying the computation through to a certain point entailing considerable work." However, the graphic method is sensitive to errors in marking off measurements, and to lack of precision in connecting marked points, etc., when preparing the diagram. Hence, until some experience and practice have been had the usual accuracy of the method, about one minute, should be increased to (say) five minutes, especially when using the diagram designed for predicting the circumstances of all occultations visible at a particular place.

Part of the uncertainty is unavoidable, because the star may disappear behind a lunar mountain or a valley which may affect the time of an occultation by several seconds. This fact, however, does not excuse the observer from accuracy in timing and in knowing his geographical position for, as remarked by Prof. E. W. Brown,[2] "Owing to the roughness of the moon's surface, observations of the same star from positions which differ only a few miles in geographic latitude are practically independent so far as the principal errors are concerned."

It is commonly believed that only observations of disappearances at the dark limb of the moon are needed. That is not the case. "Observations of reappearances at the dark limb, as well as disappearances, are of value in providing a better separation of errors in the moon's tabular longitude and in the adopted semi-diameter and parallactic inequality. Observations of phenomena at the bright limb are required in order to disentangle the errors in the adopted semi-diameter and parallactic inequality, as these cannot well be separated from one another by observations at the dark limb only. Observations of occultations therefore have their greatest value if disappearances and reappearances at both bright and dark limbs are observed."[3]

[2]E. W. Brown: Request for more Observations of Occultations; *Pop. Ast.*, 1927, 1935. See also his Practical Astronomy for Amateurs; this JOURNAL, vol. 24, 177, 1930. This paper presents curves showing the observed irregularities in the moon's position from 1650 to 1921.

[3]The Prediction and Reduction of Occultations, *Supplement to the Nautical Almanac* for 1938; H.M. Stationery Office, London.

The method of finding the circumstances of an occultation is due to Bessel.[4] Instead of the observer, from his position on the earth, watching the eastward-moving moon occult the star, Bessel imagined him to be situated on the star watching the moon overtake, occult and pass away from his earthly location which is also moving eastward, though more slowly, as the earth rotates.

The work of predicting and reducing an occultation is greatly simplified by this conception. Because of the vast distance of the star from the earth and the moon: (1) only the relative motion of the moon and the observer's real place on the earth need be considered; (2) the orbital motion of the earth can be neglected; (3) for the purposes of prediction the moon's path can be considered as straight; (4) the rays of light reaching the earth from the star being parallel instead of converging as in an eclipse of the sun, *a*, there is no penumbra, *b*, the moon's shadow, instead of being a cone, is a cylinder having the same diameter as the moon, its axis being parallel to the line of sight from the star through the centre of the earth; (5) the globe of the earth can be replaced by a circle of suitable diameter drawn upon a plane (termed the "fundamental plane" because of its importance in the theory of eclipses and occultations) which passes through the centre of the earth at right angles to the line of sight from the star; (6) finally, the moon itself can be forgotten and only its shadow-disc, moving eastward across the fundamental plane, need be considered.

The conditions described are illustrated in isometric projection in Fig. 2A. In this projection the curve *NESW* is the appearance of the circle representing the earth on the fundamental plane and *ZO* is the line of sight from the star to the centre of the earth. Similarly, the small blackened area *M'* is the foreshortened disc of the shadow of the moon *M* cast by the star. The axis of the moon's shadow is parallel to *ZO* and its radius, in terms of the earth's radius, is 1080/3965 or 0.2725.

[4]Friedrich Wilhelm Bessel (1784-1846), German astronomer, is said to have begun the study of mathematics, navigation and astronomy in order to obtain a post as supercargo on a foreign voyage, quite unnecessary accomplishments for such a post, by the way. Appointed director of the newly completed Königsberg Observatory in 1813, Bessel "inaugurated the modern era of practical astronomy."—*Enc. Brit.*, Art. Bessel.

Let two axes be drawn at right angles through the centre O of the earth-circle on the fundamental plane; one, XX', being the intersection with it of the plane of the equator; the other, YY', the projection on it of the hour circle of the star. When the centre of the moon, in its eastward course, crosses this hour circle, the moon is said to be in conjunction with the star. By reference to these axes, hour angles[5] from the hour circle of the star and the position

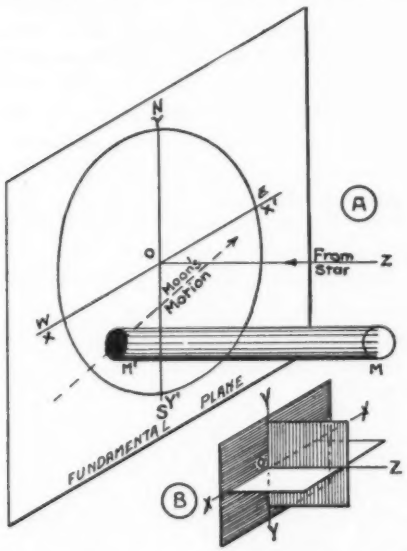

Fig. 2.—A, Bessel's method of describing an occultation (adapted from L. S. Barnes). B, The three planes of reference.

of any point or line on the fundamental plane can be defined. By convention, directions from the centre O are positive toward the east and north.

Sometimes it is more convenient to refer to the three planes which mark these axes by their intersection than to the axes

[5]The hour angle of an object is the time which has elapsed since it crossed a specified meridian. An hour angle is positive if it increases with the lapse of time.

themselves. These, see Fig. 2B, are the XY-plane, the fundamental plane of Fig. 2A; the YZ-plane, containing the line of sight from the star; and the XZ-plane, which contains the projection of the declination circle of the star.

As seen from a point in space, the apparent motion of a place on the earth may be in a circle, a straight line or an ellipse, depending, respectively, on whether the observer be stationed on an extension of the earth's axis, on the plane of the equator or at some intermediate point. In the first case the speed would be constant, but in the second and third cases the place would appear to start from rest on the western limb of the earth, increase its speed toward the centre of its journey and slow to a stop as it sets on the east limb. If a globe of the earth while being rotated be observed from positions similar to those described, places upon it will appear to move in the manner described. It can be seen also that in the case of the elliptic path the visible portion is always concave to the position of the observer.

The shape and position of the path of the place as it is projected on the fundamental plane thus depend upon two factors: the latitude of the place and the declination of the star. Its dimensions, used in drawing the diagram of an occultation, are obtained by the equations:

$$a = r \cos \varphi, \text{ and } b = r \sin \varphi \cos \delta,$$

where a is the semi-major axis and b the semi-minor axis of the ellipse, and r the equatorial radius of the earth, which is taken as unity. The derivation of these and other equations and formulæ used in this paper is given later.[6]

Selection of Occultations

Many conditions limit the number of occultations visible throughout the world. First is the range of declination outside which stars cannot be occulted. It is determined by three factors.

In Fig. 3 let OO be the trace of the earth's orbit lying at right angles to the plane of the paper. Let WS and SS be the earth at

[6]The relationship between the three types of path may be recognized by noting that a circle is an ellipse in which the major and minor axes are equal and a straight line, a "line ellipse," one whose minor axis is zero.

the winter and summer solstices; *NS* be the earth's axis and *EQ* the trace of the plane of the equator, also lying at right angles to the paper and inclined at an angle ϵ of about 23.5 degrees from the orbit plane *OO*. Then, first: at midnight at the summer solstice the intersection of the observer's meridian and the orbit plane will be about 23.5 degrees north of the equator and at the winter solstice about 23.5 degrees south of the equator. Second: the plane of the moon's orbit is variably inclined from the earth's orbit by an angle which reaches a maximum of about 5.3 degrees. Third: as the occultation is not observed from the centre of the earth but from a point on its surface, the range must be further increased by the moon's parallax, π which is about one degree.[7]

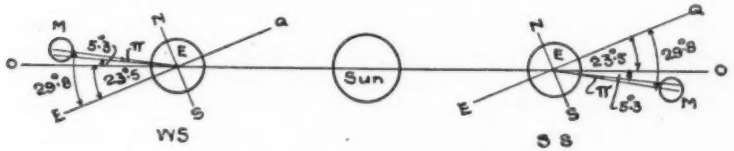

Fig. 3.—Range in declination of occultable stars.

As it is possible for these three angles to add together in both directions, the total range of declination within which a star can be occulted is $2(23.5 + 5.3 + 1)$ degrees or about 60 degrees.

Of the vast number of stars in this belt sixty degrees wide, most are too faint for an occultation to be visible. Half of the remaining occultations occur in daytime. Of the rest, some take place when the star is too close to the horizon or is too close to the New Moon or Full Moon or is covered by too small a fraction of the moon's disc to be of scientific value. Because of these conditions the total number of occultations observable throughout the world is not large, some 1500 to 2000 in a year, but not more than about five per cent of them may be visible from any one place. Moreover, the number locally visible will be reduced further by unfavourable weather and other local circumstances. It is the more important then that the few occultations actually observable be included in

[7]Because of the eccentricity of the moon's orbit her parallax varies from about 53′.8 to 61′.5.

the observing programme of every amateur. That this co-operation is needed was emphasized by the Astronomer Royal when granting permission to use certain quotations in this paper: "The observation of occultations is a field of work in which the amateur can make a very useful contribution to astronomy."

The basic data for all occultations that may be visible throughout the civilized world are published in the pages of "Elements of Occultations" in *The American Ephemeris* and *The Nautical Almanac.* Lists are included of occultations that may be visible at certain important places and correction factors "a" and "b" are added which extend the data to serve within a radius of about 200 miles. In general, however, occultations for the observing list must be selected from those in the "Elements of Occultations."

In both almanacs the pages of these elements are divided vertically by a heavy line. On the left of the line are the name or catalogue number of the star, its magnitude and position. The five columns on the right, headed T or T_0, H, Y, x' and y' are the elements of the occultation. The sixth column in the *American Ephemeris* gives the limiting parallels of latitude, and in the *Nautical Almanac* a key letter indicating the area, within which the occultation will be visible or rather outside which it will not be visible, for the limits are so wide as to be of little use in selecting occultations for the observing list.

The element T or T_0 is the instant in Greenwich mean time[8] when moon and star will be on the same meridian or "in geocentric conjunction." This meridian is represented on the fundamental plane by the Y-axis, Fig. 2A. Its hour angle from the meridian of Greenwich is H.

An occultation listed in the elements cannot be visible unless (1) the observer's meridian is within three hours of the meridian of conjunction, H; (2) the moon moving eastward in its orbit passes between the observer and the star. The elements H, Y, x' and y' enable these points to be examined.

Y, the "intercept" or intersection of the moon's path with the

[8]The Ephemeris uses both "Universal Time," U.T., and "Greenwich Civil Time," G.C.T., to mean Greenwich Mean Time and "Local Civil Time", L.C.T., to mean Local Mean Time. It must be remembered that neither Greenwich Civil Time nor Local Civil Time are the times used by civilians.

Y-axis, is the distance north or south of the point O. The slope of the moon's path upon the fundamental plane is determined by x' and y'. These are respectively the changes in one hour in the moon's right ascension and declination at the time T. The lengths of Y, x' and y' are given as fractions of the earth's radius, not because it is a certain number of miles or kilometers long but because it is the measure of the moon's parallax which is the real basis for all measurements on the occultation diagram.

Certain limits govern the inclusion of an occultation in the list in the almanacs. To quote from the *Nautical Almanac*, 1938, p. 850:

> Elements . . . are not given within 48 hours of New Moon. Stars fainter than magnitude 3.0 are excluded for 24 hours and fainter than magnitude 5.5 for 48 hours before and after Full Moon. Stars fainter than magnitude 6.5 are included from 48 hours after New Moon to 72 hours before Full Moon.
>
> 1. *Limb.* At the bright limb disappearances are given only for stars of magnitude 4.5 or brighter and reappearances only for stars of magnitude 3.5 or brighter.
>
> 2. *Daylight.* Predictions are given for stars and planets of the first magnitude for daylight hours when it appears that their observation may be possible: For other stars the earliest and latest times for which predictions are given are.

Magnitude	*Limits in West*	*Limits in East*
4.5 or brighter	Sunset	Sun 6° below horizon
4.6—5.5	Sun 3° below horizon	Sun 9° below horizon
5.6—7.5	Sun 6° below horizon	Sun 12° below horizon

> 3. *Altitude.* The star is at least 10° above the horizon at the time of occultation—p. 852.

Instead of specifying the minimum altitude of the star the *American Ephemeris* excludes occultations when the hour angle $H-\lambda$ between the star and the observer at the time T, "taken without regard to sign"; that is, either west or east of the Y-axis, "is not at least one hour less than the semi-diurnal arc of the star." This criterion means that the star must have been above the horizon for at least one hour. Local conditions may make it necessary to increase this margin.

The diurnal arc, t, of a star is that portion of its daily circuit of the sky during which it is above the true or the astronomical horizon. Thus it depends upon the latitude φ of the place and the declination δ' of the star. Its projection on the fundamental

plane is the same as the elliptical path of the place and it is similarly bisected by the Y-axis.

The semi-diurnal arc can be read off the occultation diagram, but preferably is computed from the expression

$$\cos t = \mp \tan \varphi \tan \delta'.$$

The upper sign applies when latitude and declination have the same name, are both north or both south. The time t is then negative and is to be subtracted from 12 hours. When latitude and declination have opposite names t is positive and is the semi-diurnal arc required.

Example.—For an observer in latitude 48° N. find the semi-diurnal arcs of two stars whose respective declinations are $+16°$ and $-16°$.

Here $\tan \varphi = 1.1106$, $\tan \delta' = 0.2867$, whence $\cos t = \mp 0.3184$ and $t = \mp 71°34'$. Turning this into time, $t = \mp 4^h45^m.7$. Whence the semi-diurnal arc of the northern star is $12^h - 4^h45^m.7 = 7^h14^m.3$ and of the southern star is $4^h45^m.7$.[9]

For latitudes between 32° and 60° a curve of the semi-diurnal arcs of occultable stars can be prepared having sufficient accuracy for selection purposes by interpolation from the family of such curves in Fig. 4, drawn for northern latitudes. A scale can be added at the centre line of the figure from which can be read directly the semi-diurnal arc minus the margin of an hour or more necessary for the star to be high enough above the horizon for observing.

Local conditions also limit the number of occultations suitable for the observing list.

Observing period. If t_1 to t_2 be the available observing period in (twenty-four hour) standard time for an observer in west longitude λ, the corresponding period in G.M.T. will be from $\lambda + t_1$ to $\lambda + t_2$. As an occultation cannot occur more than three hours from the G.M.T. of conjunction, T_0 (*N.A. Supp.*, p. 38), the extreme range of T_0 for which one or other phase of an occultation may be visible is from $T_0 = \lambda + t_1 - 3h$ for a reappearance to

[9]When the exact time of rising or setting is wanted, t as computed above must be corrected for refraction by one of the several approximate formulæ, such as $t_r = r \sin q \sec \delta'/15$, where q is the parallactic angle of the star, δ' its declination and r the refraction at the horizon, about 35′.

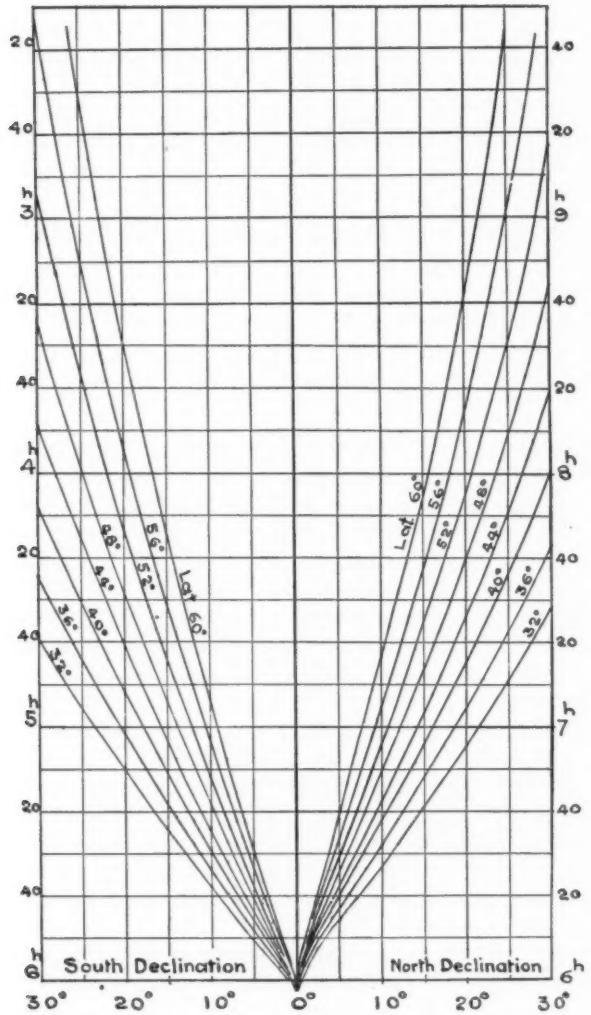

Fig. 4.—Semi-diurnal arcs.

$T_0 = \lambda + t_2 + 3h$ for a disappearance. Thus for an observer in longitude 96°, or 6^h24^m west, observing on January 5 between 6.00 p.m. and 11.00 p.m. M.S.T. (18^h to 23^h), the range of T_0 will be from Jan. $5^d21^h24^m$ to Jan. $6^d8^h24^m$ G.M.T.

Value of H. For an occultation to be visible from a specified position the hour angle H of the meridian of conjunction must lie within certain limits. The visibility condition can be written

$$H - \lambda \gtrless t - h \qquad \text{(a)}$$

where H is the hour angle from Greenwich of the meridian of conjunction, λ the longitude of the position, t the semi-diurnal arc of the star and h the allowance for altitude.

Transposing λ we may write for the maximum and minimum values of H:

$$H_{max} = \lambda + (t - h) \qquad \text{(b)}$$

$$H_{min} = \lambda - (t - h) \qquad \text{(c)}$$

When H exceeds 12 hours it is to be subtracted from 24 hours. The remainder, given the opposite sign, is the value required. Curves of the limit values of H plotted against the declinations of occultable stars as in Fig. 5 are convenient when selecting occultations for the observing list.

Value of Y. The use of Y, the intercept of the moon's path with the Y-axis, to indicate the visibility of an occultation is severely limited by two independent factors (1) the great variation in the slope of the path and (2) in the position and shape of the place-ellipse.

When these factors are known, or can be assumed, arbitrary limits can be set for the value of Y that will include all occultations that may be visible from a specified position. The test is not decisive, for not all occultations will be certainly visible for which Y is within the indicated limits. However, together with the limit values of H, it will enable a number of occultations to be excluded on inspection that otherwise would need examination by means of the general diagram.

It follows from Fig. 3 that the maximum angle of the moon's orbit plane from the plane of the equator cannot exceed 30°. As the X-axis is the trace of the equator on the fundamental plane the moon's path cannot slope more than 30° from the X-axis.

Approximate limits for Y consequently can be determined for each ellipse by drawing two lines to cut the Y-axis at opposite slopes of 30° from the X-axis. One line is drawn tangent to the

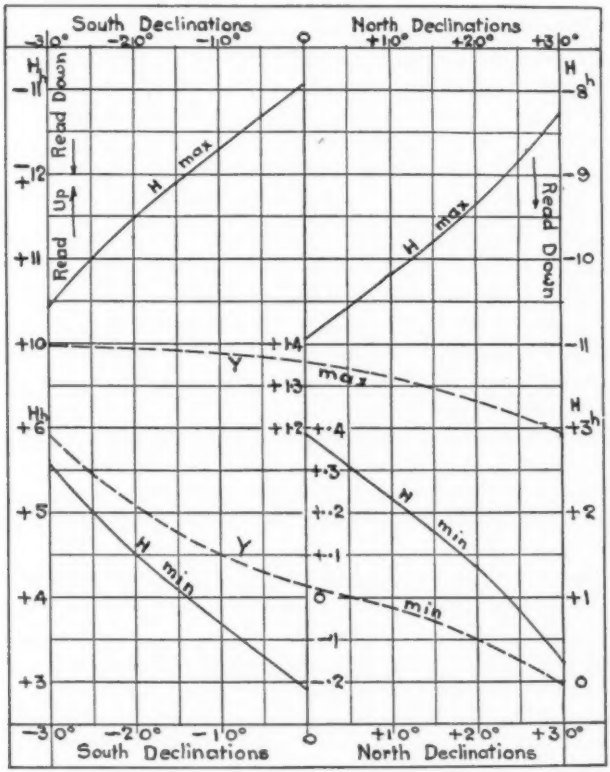

Fig. 5.—Limiting values of H and Y for latitude 48°.

ellipse, the other at the opposite slope through a point arbitrarily taken at 5 hours from the Y-axis. The points where these lines cut the Y-axis plus or minus 0.254 are the maximum and minimum values of Y for that ellipse.

The constant 0.254 is arrived at as follows: For reasons discussed later the half width of the moon's path may be taken at 0.220 instead of 0.273 of the earth's radius. Then

$$0.220/\cos 30^\circ = 0.254$$

which is the length of the projection on the Y-axis of the half-width of the moon's path when the slope is 30° from the X-axis.

Once determined for a particular position, these limits can be plotted against the declinations of occultable stars as in Fig. 5 where the altitude allowance has been taken at one hour.

Construction of the Diagram

For drawing the diagram for the graphic prediction of the circumstances of an occultation there are needed the ordinary drawing instruments, a small celluloid protractor, an "engineer's" scale (inches divided into tenths, twentieths, etc.), a good table of 5-figure logarithms and trigonometric functions, natural and logarithmic[10] and the issue of the *American Ephemeris* or the *Nautical Almanac* for the year.

There are two forms of the diagram: one for a single occultation; the other, the general diagram by which the circumstances of all occultations visible in a prescribed latitude are determined. The first form, chiefly useful to explain the method and meaning of the second, is now described.

Perhaps the best way to become familiar with the work is to follow an actual example. The details of this description were written step by step as the diagram, Fig. 6, was being drawn. It is suggested that the reader draw the diagram as he reads, checking his work with the figure as he proceeds.

The scale of the diagram must be settled first. The unit for all measurements on the diagram is the earth's radius. A radius of 5-in. is convenient as the drawing can then be put on an $8\frac{1}{2} \times 11$ in. sheet of paper. With this radius each small division of the twenty-to-the-inch scale represents one-hundredth of the earth's radius, which can be laid off to the thousandth with sufficient accuracy for the purpose by estimating tenths of these divisions. A reading glass is useful for this work.

[10]Hussey's *Mathematical Tables*; Allyn and Bacon, New York, are suitable.

The place of observation is assumed to be at latitude φ 43°40′N; longitude λ 79°23′30″ or $5^h17^m34^s$ west. The occulted star is Aldebaran, α Tauri; the date 1943, January 16. The moon's age is 10.6 days, so that disappearance takes place at the dark limb.

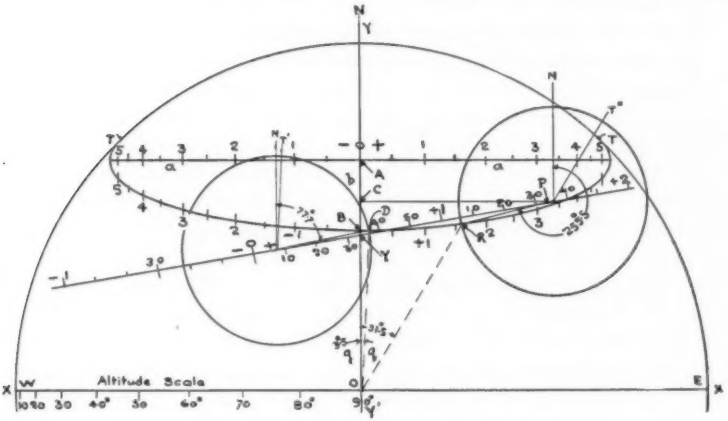

Fig. 6.—Diagram for a single occultation.

The Elements of the occultation, taken from the *Nautical Almanac* are:

Star N.Z.C. 692	α Tauri
Right Ascension	$4^h\,32^m\,39^s.4$
Declination, δ'	16° 23′ 38″.8
G.M.T. of Conjunction, T_0	Jan. $17^d\,02^h\,41^m.5$
Greenwich hour angle of meridian of conjunction H, reckoned + to west, − to east	$+\,5^h\,51^m.4$
Intercept of the moon's path with the Y-axis Y	+ 0.453
Moon's hourly motion in RA, x'	0.541
Moon's hourly motion in declination y'	+ 0.093

Motion in right ascension is always eastward, to the right on the diagram.

From the trigonometric tables take out

sin φ	0.6905	sin δ'	0.2822
cos φ	0.7234	cos δ'	0.9593
tan φ	1.0477	tan δ'	0.2942

1. With 5-in. radius draw the circle *WTTE*, Fig. 6, representing the projection of the earth on the fundamental plane. Through the centre *O* draw the horizontal axis *XX* and the vertical axis *YY*. Mark on them the compass points as on a map. North at the top, west at the left.

2. *The elliptic path of the place.* The ordinate of the centre of the ellipse, the distance of the centre from *O*, is sin φ cos δ', 0.6905 × 0.9593 or 0.6624. Four figures should be used in the computation although, as values can be plotted to three figures only because of the small scale, three may be used. The place being north of the equator, the ordinate of the centre is laid off northward from *O* to *A* on the *Y*-axis. The major axis is then drawn through *A*, parallel to the *X*-axis. Its half length, *a*, is equal to cos φ, here cos 43°40′, or 0.7234, and is marked off on each side of the *Y*-axis.

The length of the semi-minor axis *b* is equal to cos φ sin δ', or 0.7234 × 0.2822 which is 0.2041. The declination of the star being positive or north, the portion of the ellipse visible from the star will lie to the south of the major axis. Accordingly the semi-minor axis, 0.204, is marked off southward on the *Y*-axis from *A* to *B*.[11]

Other points on the ellipse of the place are now fixed by their abscissæ, distances from the point *A* along each half of the major axis, and ordinates, distances from the major axis, here being downward. The standard symbols for these quantitities are ξ for the abscissæ and η for the ordinates. They are computed from the relations.

$$\text{Abscissæ } \xi = \cos\varphi \sin t$$
$$\text{Ordinates } \eta = \sin\varphi \cos\delta' \cos t,$$

where *t* is the hour angle of the point from the *Y*-axis.

As an example, the computation of ξ and η for the hour angle $t = 2.5$ hours follows.

Converted into arc, 2.5 hours equals 37°30′. From the tables take out sin *t*, sin 37°30′; 0.6088 and cos *t*, cos 37°30′ or 0.7934. Then

$$\xi = 0.7234 \times 0.6088 = 0.440$$
$$\eta = 0.6095 \times 0.9593 \times 0.7934 = 0.162$$

The required number of abscissæ (half-hour intervals are generally sufficient) are marked off on the major axis on both sides of the *Y*-axis and lines parallel to the *Y*-axis are drawn through

[11]The letters designating certain points are not needed in practice.

the points. The length of the corresponding ordinate is then marked off (here downward) from the major axis.

The points where the ellipse becomes tangent to the earth circle, here about $t = 7^h10^m$, are points on the observer's true or astronomical horizon. Neglecting refraction, they are the points where the place is seen from the star to rise and set or where the star will rise and set as seen from the place. These points are computed from the expressions

$$\cos t = -\tan \varphi \tan \delta'$$
$$\eta = \sin \varphi \sec \delta'.$$

Having plotted the points a smooth curve is drawn through them, completing the ellipse.

3. *The Moon's Path.* Provided that when plotted on the diagram the position of the moon's path and the distance travelled along it by the moon in one hour shall be correctly laid down, the manner of plotting the x' and y' coordinates is largely a matter of individual preference. Rigge, to be able to plot y' on the Y-axis plots x' on the X-axis to the left from O; that is, in the opposite direction to the moon's motion. Having joined x' and y' he then draws the path through the intercept Y parallel to the line $x'y'$. A second way is to plot x' in its true direction, eastward from O and y' from the eastern end of Ox' upward if positive downward if negative, join x' and y' and draw the path parallel to $x'y'$ through Y as before. A third and, in the writer's view, the most accurate method is the following:

On the Y-axis mark off the values of Y and $Y \pm y'$ as y' is positive or negative, see the point C (Fig. 6). Through C draw CP eastward parallel to the X-axis and mark on it the given value of x'. Draw YP and extend it a short distance beyond the circumference of the earth-circle to M and M'. Then MM' is the centre line of the moon's path and the length YP is the distance travelled along it by the moon in one hour.

In the diagram for α Tauri (Fig. 6), Y is $+0.453$, y' is $+0.093$ and $Y + y'$ is $+0.546$; x' is 0.541.

The moon's path is now to be graduated in time, or, more correctly, in hour angle. The length YP is marked on the straight edge of a strip of paper, the marked distance fitted to the outside lines of a grid such as in Fig. 7, and the corresponding five-minute

divisions transferred to the strip from the grid.[12] The graduated length is then used to subdivide the moon's path.

The starting point of the graduation is the value $H - \lambda$, the hour angle of the moon from the place. In our example the longitude of the place λ is $5^h17^m.6$ west from Greenwich. At the instant of conjunction the moon's hour angle from Greenwich H is $5^h51^m.4$, also west from Greenwich. Accordingly the moon must be $5^h51^m.4$ minus $5^h17^m.6$ or $33^m.8$ west of the place. That is, when the place is on the Y-axis the moon is $33^m.8$ west of it. Consequently

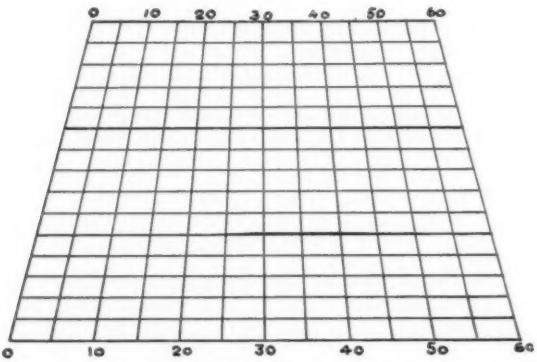

Fig. 7—Grid for subdividing Moon's path.

the graduated edge of the paper strip must be applied to the moon's path so that the zero, 0 hours, lies $33^m.8$ to the west of the Y-axis. The graduations are then transferred from the strip to the path for about three hours on each side of the Y-axis. West of the zero on the path the hour angles are negative as seen from the star, east of that point they are positive.

Now that the courses, so to say, of moon and place are laid out, it is well to recall that the diagram is a substitute for a moving picture of events. Looking down on the diagram as from the star

[12]Rigge (in The Graphic Prediction of Eclipses and Occultations, Loyola Univ. Press) recommends that the greatest and least widths of the grid be 0.65 and 0.50 of the earth's radius. The horizontal lines on the grid are merely guides to ensure the strip is correctly placed on the grid. (Rigge, p. 64.)

the observer moves the moon eastward along its path until the eastern limb overtakes and covers the place, also moving eastward along its elliptical path. This occurs when the hour angle of the moon's centre, measured by the graduations on its path, is the same as the hour angle of the place from the Y-axis as measured by the graduations on the ellipse. This is the hour angle of disappearance. After an interval, as the moon continues on its way the western limb uncovers the place in its then position. This occurs when the hour angles of the moon and the place are again equal. This is the hour angle of reappearance. These hour angles converted into standard time are the times when the phases of disappearance and reappearance will be visible from the observer's position.

The simplest way to determine the hour angles of the phases is by means of a pair of dividers opened to the radius of the moon, i.e., 0.273 of the earth's radius. With one point following the place on the ellipse and the other the centre line of the moon's path the dividers are moved eastward until the same hour angles, both positive or negative, are reached on both lines. If the point of tangency of the ellipse with the earth circle is reached before a second pair of equal hour angles, the star is still occulted as it sets.

Because the moon moves eastward faster than the place the scale on the moon's path is more open than that on the ellipse. Consequently the minutes of the hour angles are more easily read from the graduations on the moon's path.

In our example the hour angles were read as

Disappearance $+ 0^h 07^m.0$
Reappearance $+ 1^h 36\ .0.$

The hour angles are converted into the corresponding standard times at the place as follows: At the instant of conjunction the star is on the observer's meridian. Hence the observer's local mean time is $H - T_0$. The phase of the occultation occurs when the star is at some positive or negative hour angle t from the observer's meridian. Hence the local mean time of that phase is $H - T \pm t$; plus t if the observer is east of the Y-axis, minus t if he is west of it. The local mean time is converted into standard time by correcting it for the observer's difference of longitude $\Delta\lambda$ from the standard time meridian.

In the example we have

T_0 G.M.T. of conjunction	Jan. 17^d	02^h	$41^m.5$
H, Hour angle of star		5	51.4
LMT on meridian of conjunction	16	20	50.1
t, hour angle of disappearance			+07.0
LMT of disappearance	16	20	57.1
$\Delta\lambda$			+17.6
Standard time of disappearance	16	21	14.7
Similarly computed the standard time of reappearance was	16	22	43.7

The times given in the *Observer's Handbook* and in the *Nautical Almanac* are

Disappearance.....$16^d\ 21^h\ 13.^m7$, diff. $+1^m.0$

Reappearance.....$16^d\ 22^h\ 43^m.0$, diff. $+0^m.7$

Two points sometimes cause difficulty. (1) There is the apparent discrepancy in the manner of measuring the hour angles; one to the moon's centre, the other to the limb. There is no discrepancy however. The latter angle is not measured to the limb of the moon but to the place on the ellipse. Both angles are measured from the zero points of the respective graduations; points on the ellipse from the Y-axis and the point at the hour angle $H - \lambda$ for the centre of the moon. (2) The hour angle H is expressed in sidereal time while λ is in mean solar time. The measurements being made in different units, $H - \lambda$ is not a correct operation. Since the times of the phases are wanted in mean solar time, should not H be converted into mean time before taking the difference? This is true but, as has been seen, when the hour angles of the phases are converted into mean time, H is subtracted from T, which involves a precisely equal but opposite correction. Since the two corrections thus cancel one another both can be omitted.

Position Angles. As the star can be seen up to the instant of disappearance, only the time of this phase is needed from the diagram unless the altitude of the star is needed also. For reappearances, however, the point on the limb must be closely known if the eye strain of watching for it and a probable large error in timing are to be avoided. So little additional work is needed that, if only for the sake of completing the data, the position angles and

altitudes of the star at both phases should be ascertained as well as the times.

The positions of the points on the moon's limb where the star will vanish and reappear are fixed by reference to one of two easily recognizable points depending upon the instrument used when observing: (1) the vertex or top point, and (2) the north point. With a field glass or altazimuth telescope the vertex must be used. When a properly oriented equatorial is available the north point is more convenient.

Owing to the rotation of the earth, the relative positions of these points change as the moon moves across the sky. The north point is to the east of the vertex while approaching the meridian but to the west of it after passing the meridian. The angle at the centre of the disc between vertex and north point is called the "parallactic angle," symbol q. In occultation work this angle is defined as the angle at O, the centre of the earth on the fundamental plane between the Y-axis and the observer's position, as seen from the star. It is measured eastward or clockwise on the diagram.

The reference points and position angles are fixed on the diagram as follows:

With centres on the moon's path at the hour angles of the phases and with the moon's radius, 0.273, draw circles to represent the moon in its two positions. Then (1) lines drawn through the centre of each circle parallel to the Y-axis (northward), cut the circumferences in the respective north points N. (2) From the centre of the earth draw the lines OD and OR to the phase points. Then the angles YOD and YOR are the parallactic angles at the times of the phases. Lines drawn through the centres of each circle parallel to OD and OR cut the circumferences in the respective top points T' and T''. (3) Arcs measured eastward or clockwise from the reference point used to the phase points are the position angles required.

In the diagram the position angles read with a protractor from the north point were: disappearance 77.7°, reappearance 255.5°. The angles given in the *Observer's Handbook* are 80° and 254°.

Altitude. The altitude of the star is quickly found. As shown later, the length of OD or OR, expressed as a fraction of the earth's radius, is equal to the cosine of the angle of altitude h. In the

diagram OD or cos h is 0.462, whence the altitude of the star at disappearance is about 62.5 degrees.

If a scale of cosines be prepared similar to that on the left half of the X-axis, the altitude can be read directly off the diagram.

The All Occultation Diagram

The diagram for a single occultation must be modified considerably before it can be used for predicting the circumstances of all occultations that may be visible from a particular latitude.

1. Instead of one ellipse it must contain a sufficient number so that the path of a place in that latitude, as seen from any star within the occultable zone (between declinations $\pm 30°$), can be correctly interpolated.

2. Because of the wide variation in the point of its intercept with the Y-axis and also in its slope, the moon's path cannot be drawn on the diagram but must be fixed by one of the methods described below.

3. Provision must be made that for each occultation the moon's path can be graduated correctly.

4. The circumstances of all occultations must be obtainable more quickly and easily than by specially drawn diagrams but with practically equal accuracy.

The circle representing the projection of the earth to the selected scale, radius 5-in., and the X- and Y-axes are drawn through the centre as in the single diagram. In this case both axes are graduated in terms of the earth's radius, using the 20-to-the-inch scale; the X-axis from 0.400 to 0.650 from the centre O and for the Y-axis from -0.200 to $+1.400$ (see Fig. 8, which has been computed for a standard latitude of 48°).

Place-ellipses. In the figure the series of place-ellipses is drawn at four-degree intervals. The usual interval is five degrees. Seven ellipses are needed on each side of the 0° line-ellipse instead of six but interpolation is made easier. For declinations greater than 28 degrees the position can be extrapolated, or the ellipses for 30 degrees can be drawn in. Ellipses for the same northern and southern declinations are the same and have the same ordinate of the centre.

The length of the semi-major axes a, and the hour angle graduations are the same for all ellipses. The position of the centre and the length of the semi-minor axes b, however, must be computed for each ellipse as both depend upon the declination for which the ellipse is drawn.

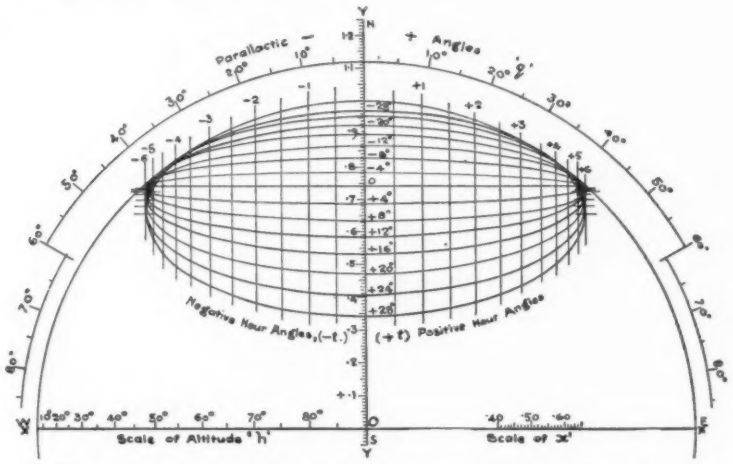

Fig. 8.—Diagram for determining the circumstances of all occultations visible from a particular latitude.

The equations for computing these values, the earth's radius being taken unity, are:

Ordinate of the centre = $\sin \varphi \cos \delta'$
Semi major axis a = $\cos \varphi$
Semi minor axis b = $\cos \varphi \sin \delta'$
Hour angles abscissæ = $\cos \varphi \sin t$
ordinates = $\cos \varphi \sin \delta' \cos t$

Where φ is the latitude
δ' the declination of the star
t an hour angle.

The major axes of the ellipses, being merely construction lines, may be put in in pencil and erased when the diagram is finished or the ends inked in as in the figure. The ellipses can be drawn in by hand or with a "French curve" but are better put in with a

ruling pen guided by templets cut from stiff cardboard. The diagram is then more accurate, much neater and correspondingly easier to use.

The Moon's Path. The methods adopted for fixing the path of the moon's centre are unnecessarily complicated. Rigge's method is this: The straight edge of a strip of paper about a foot long is applied to the X- and Y-axes at the given values of x' and y' and the distance between these points marked on it. The strip is then graduated by means of a grid as for the single diagram but the graduations are extended for about five to six hours. The strip, which now represents the centre line of the moon's path, is then replaced on the diagram, touching the points x' and y' as before. By the aid of a straight edge and set square it is now moved parallel to itself and endwise until the graduated edge cuts the Y-axis at the correct slope and hour angle and is weighted to prevent it from being moved.

The moon, represented by a circle of radius 0.273 scribed in square of celluloid, is now slid eastward along the edge of the paper to determine the hour angles of the phases, thus taking the place of the dividers used in the case of the single occultation diagram.

In Mrs. Lewis's method which, it must be remembered, was devised for use for any place and time, Rigge's paper strip is replaced by a similar strip of celluloid some 12 inches long and with width equal to the diameter of the moon on the scale used. The centre line of the strip is graduated in millimetres (a radius of 10 cm. is used for the earth by Mrs. Lewis) and circles with the moon's diameter are scribed at each end and in the middle of the strip and graduated in single degrees for estimating position angles.

The X- and Y-axes are graduated similarly to Rigge's method except that when the value of y' is small the values of x' are laid off "on a line several centimetres below the X-axis and parallel to it instead of on the X-axis," the values of y' being measured "north or south from the point of intersection of this line with the Y-axis to avoid conflicting with the strip representing the moon's path."

The slope of the path is defined by means of a straight edge placed to intersect the axes at the given values of x' and y'. The celluloid strip is brought up to touch the straight edge and is then

moved parallel to itself and endwise until the centre lies on the Y-axis at the value of the intercept for the occultation being examined, which is always measured from the point O, not from the auxiliary line.

So far, this method, although it requires more preliminary work than Rigge's, has the advantage of indicating at once whether the star will be occulted. Unless the edge of the lunar strip intersects the ellipse along which the place is moving an occultation clearly is impossible. If an intersection occurs the circumstances of the occultation are determined by finding the same hour angles on the ellipse and the moon's path. Those of the place are readily obtained from the time-points common to all ellipses on the diagram, but as the moon's path is graduated not in time but in millimetres the corresponding angles on it cannot be read off directly but must be computed by taking the ratio of the distance of the point required, measured along the path to the Y-axis, to the distance $x'y'$ travelled by the moon in one hour, both measured in millimetres and subsequently reduced to proportional times.

When the width of the lunar strip represents the full diameter of the moon, although an occultation may be shown to occur by the edge of the strip touching or overlapping the place-ellipse, unless the overlap exceeds a certain minimum, the occultation will be merely a graze and of no scientific value.[13]

Let the necessary overlap be one-fifth of the moon's radius, corresponding to an occultation lasting about thirty-six minutes. This requirement can be met by reducing the width of the strip from 0.273 to 0.218 or, say, to 0.220 of the earth's radius. If now the edge of the strip touches or overlaps the appropriate ellipse when correctly placed on the diagram a useful occultation will occur.

The practical difficulty in both of these methods lies in insuring that the lunar strip remains parallel to the line $x'y'$ while being moved to its required position. Rigge, recognizing the difficulty, suggests (*loc. cit.*, p. 63) "the use of one or more artifices" singly or in combination "to reduce the risk of not moving it parallel to

[13]The *Nautical Almanac* excludes as grazes occultations lasting less than thirty minutes.

itself," which is only part of the problem for it must be moved endwise as well.

The method now to be described avoids the difficulties mentioned. It requires little if any more time to carry out and has the merit of providing a record every step of which can be checked. The small amount of drawing needed is shown in Fig. 9.

A sheet of tracing paper, say $8\frac{1}{2} \times 11$ inches, is secured over the general diagram and the X- and Y-axes traced on it in pencil. Using the scales on the general diagram the centre line of the moon's path is drawn directly through the intercept as was done on the diagram for the single occultation (Fig. 6), and a line is drawn parallel to it at the selected distance, 0.220 of the earth's radius. If it appears that this line will touch or intersect the appropriate ellipse, a useful occultation will occur. The ellipse is sketched in, using as guides the adjacent ellipses of the general diagram. In the figure these ellipses are shown by dotted lines to indicate that they are seen through the tracing paper.

The moon's path is graduated by means of a grid, the hour angles of the phases found by the dividers opened to 0.273, the full radius of the moon, and the remaining circumstances of the occultation determined as in the case of the single diagram into which this method resolves itself.

In Fig. 9 the occultation used to illustrate this method is the same as in Fig. 6, α Tauri, on Jan. $17^d02^h41^m.5$ G.M.T., but arranged as for an observer in lat. 48° N., long. 122° W. Taken from the figure the circumstances of the occultation for this position are:

Disappearance P.S.T.	Jan. $16^d\ 17^h\ 30^m.1 \pm 2^m.0$
Position angle	20°.6
Altitude	54 .7
Reappearance P.S.T.	Jan. $16^d\ 18^h\ 20^m.1$
Position angle	301°.2
Altitude	44 .8

These data can be partially checked by reducing to this position the circumstances of this occultation as given for Vancouver, B.C., taken as the standard station. The reduction is made by the equation:

$$T = T_0 + a(\lambda - \lambda_0) + b(\varphi - \varphi_0),$$

where T, λ and φ are the time of the phase and the longitude and latitude of the observer's position, and T_0, λ_0 and φ_0 those at the standard station, lat. 49°.3 N., long. 123°.1 W.

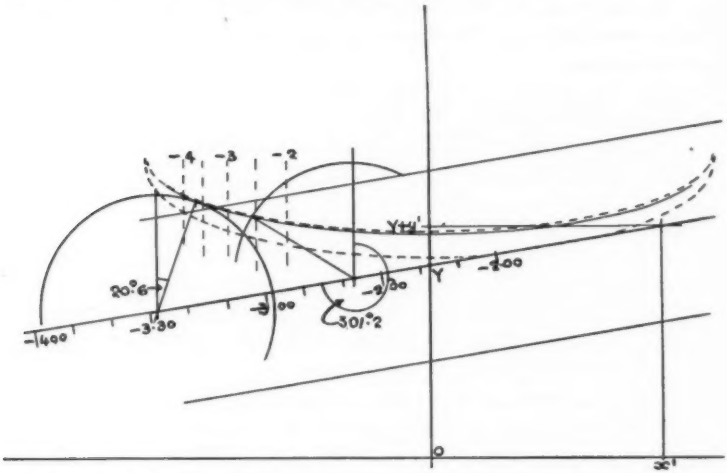

Fig. 9.—Application of suggested method of using the general diagram for determining the circumstances of an occultation.

For the standard station we have, *Observer's Handbook*, 1943, p. 59:

		a	b
Disappearance	$16^d\ 17^h\ 36^m.0$	+0.1	+3.7
Reappearance	$16^d\ 18^h\ 17^m.0$	−12.0	−0.5

Then $a(\lambda - \lambda_0) = +0.1 \times -1.1 = -0^m.1$

$b(\varphi - \varphi_0) = +3.7 \times -1.6 = -5^m.9$

Whence $T = 16^d\ 17^h\ 30^m.0$ for disappearance.

For reappearance

$a(\lambda - \lambda_0) = -2.0 \times -1.1 = +2.2$

$b(\varphi - \varphi_0) = -0.5 \times -1.6 = +0.8$

Whence $T = 16^d\ 18^h\ 20^m.0$.

The close agreement here shown is fortuitous because either prediction may be in error by a minute either way. Further, the nearly tangential approach of the moon's limb to the position of the observer makes the time of disappearance somewhat doubtful.

For this reason the allowance of ±2.0 minutes was made. Such agreement however strengthens the reliance to be placed on the graphic method of prediction.

To recapitulate: The following procedure is suggested for selecting occultations for the observing list from the Elements given in the almanacs:

1. The selector runs down the column headed T or T_0 until a time is reached within the G.M.T. limits of the observing period.

2. The values of H and Y are compared with the limits for these elements as shown by curves prepared for the place of observation similar to those in Fig. 5.

3. The age of the moon is noted.

4. If these indications are satisfactory, the elements of the occultation are copied into a list for examination with the general diagram. It is convenient to have a sheet attached to this list containing data continually needed: the geographic latitude of the place and its longitude in mean time; the G.M.T. limits of the observing period for the several seasons of the year; the correction to reduce local mean time to standard time; the allowable maximum value of $H - \lambda$ unless this is included on the curves of semi-diurnal arc as in Fig. 4.

5. The circumstances of each occultation are entered in the observing list.

Sky Diagram. A small diagram sketched beside the circumstances of the occultation in the observing list, showing the positions of the phases as they will appear in the eyepiece of the telescope is useful when preparing to observe the occultation. As the relative positions of these points in the field will change with the type of instrument, etc., these particulars must be known when the sketch is being made.

(*To be Continued*)

COMMUNICATIONS
FROM THE
DAVID DUNLAP OBSERVATORY
Number 11

DISTRIBUTION OF PERIODS OF CLUSTER TYPE VARIABLES IN GLOBULAR STAR CLUSTERS

By Helen B. Sawyer

NEARLY twelve hundred variable stars are known at present in globular star clusters.[1] The great majority of these variables are cluster type Cepheids having periods shorter than one day. Accurate periods are known for approximately 700 of these short-period variables.

The number of cluster type variables having different lengths of period in the individual clusters has been of interest since Bailey[2] first published, in 1902, a graph showing the distribution of period-lengths for the cluster Omega Centauri, which contains more than 150 variables. These he classified into three groups, a, b, and c, mainly on the basis of period-length. In Omega Centauri the most frequent periods were in the c-type group, around 9 hours, and the a-type group, at about 15 hours.

The next two clusters containing many variables, which Bailey investigated some years later, Messier 3[3] and Messier 5,[4] gave curves with a strongly pronounced maximum at half a day, midway between the two maxima of Omega Centauri. Subsequent work on Messier 15[5] revealed a type of frequency curve dissimilar to these three, having a double maximum and a gap of 0.11 day between the two groups of periods, in which gap not a single period was found. A recent paper by the writer[6] has shown another cluster of this sort, Messier 22, in which apparently such a gap exists. The gap in Messier 22, in fact, is larger than in any other cluster investigated to date. In view of this fact, it was thought expedient to summarize the existing data on this subject.

An excellent paper on the frequency of cluster type periods was published by Oosterhoff[7] in 1939, but he confined his remarks to the five relatively bright clusters which have large numbers of variables, namely Omega Centauri, M 3, M 5, M 15, and M 53. His frequency diagram was reprinted by de Sitter,[8] with the addition of Messier 4 in which de Sitter had derived many periods. Naturally a cluster in which many variables are known should have more weight in such a discussion than one containing only a handful of variables. Nevertheless the writer feels that it is desirable to present additional diagrams, especially for those clusters for which recent period-determinations have been made. There are now 7 additional clusters containing from 7 to 58 cluster type variables with known periods, which may logically be included in such a summary. The two clusters NGC 6934 and 6402 in which the writer has derived many cluster type periods, as yet unpublished, are not included because the data are still incomplete.

The data for the 13 clusters are summarized in Table I, where the numbers of cluster type periods in a given cluster are totalled in intervals of 0.05 day. The last three columns of the table give successively the total number of cluster type periods in the cluster, the number of variables known to be other than cluster type Cepheids, and the number of unknown periods. This last number is a good guide to the completeness of the investigation of each cluster. Some c-type periods of approximately one third of a day will probably be in that number, since with their small range and tendency toward period-change, they are among the more difficult periods to determine. Irregular variables also will help to compose it. For each cluster, the references used to derive the data may be found in *Pub. D.D.O.*, vol. 1, no. 4, 1939, under the individual cluster, except for later references which are indicated in the footnotes to the table.

Three clusters require special comment. For NGC 5272 the data tabulated are from unpublished results very kindly sent to the writer by Dr. W. Chr. Martin, Johannesburg, correcting or refining the existing periods. In spite of numerous small corrections and a number of large ones, the frequency curve is very little different from that plotted from published observations.

In NGC 5904 there are 13 cluster type periods corrected or determined by Oosterhoff recently, but the actual values have not yet been received in this country. Oosterhoff's paper will give the correct frequency distribution.

TABLE I

FREQUENCY OF CLUSTER TYPE PERIODS IN GLOBULAR CLUSTERS

N.G.C.	Period Range in Hundredths of a Day														No. of Vars.	
	00 to 25	25 to 30	30 to 35	35 to 40	40 to 45	45 to 50	50 to 55	55 to 60	60 to 65	65 to 70	70 to 75	75 to 80	80 to 85	Clus. Type	Others	Undet
362						2	3	1		1				7	3	4
3201		1				5	26	15	10	1				58	2	15
5024			4	11			3		10	2	2			32	0	9
5139	1	3	16	24	10	5	10	15	17	14	5	6	6	3	135	6	12
5272	0	6	14	7	3	19	63	30	18	6	1	1			168	2	14
5904	1	1	2	1	1	17	16	14	7	3	1		1		65*	4	..
6121	1	4	3		3	7	10	4	8						40	2	2
6341	2			2	1		1		5		1				12	1	3
6656			4	3	3				6	1	1				18	4	3
6723			1		2	5	9	1	1						19	0	0
6981			1	3	1	4	7	8	1	1					26	0	8
7078		1	3	18	7			9	6	11	4	1			60	1	3
7089					1	1	1	2	4	3	1				13	4	0

*More data on this cluster published but not available.

REFERENCES FOR TABLE I SUBSEQUENT TO THOSE GIVEN IN PUB. D.D.O. 1, 4, 1939.

N.G.C. 3201 Wright, H. B. 915, 1941.
N.G.C. 5024 Oosterhoff, B. A. N. 325, v, IX, p. 57, 1940.
N.G.C. 5272 Martin, Letters, Sept. 9, Dec. 3, 1940, Johannesburg.
N.G.C. 5904 Oosterhoff, Dutch Ast. News Letter 1, 1943. (Summary of Leiden Ann. XVII.)
N.G.C. 6121 de Sitter, Natuurwet. Tijds. voor Ned. Indië, dl. 101, afl. 2, 1941.
N.G.C. 6656 Sawyer, Pub. D.D.O. v. 1, no. 15, 1944.

For NGC 6981 the periods are based on fewer plates than for the other clusters and are somewhat more likely to include fictitious periods.

The data of Table I are depicted graphically in Figure 1, showing the number of variables for each period-interval. Attention has already been called to the noteworthy difference between the distribution in Omega Centauri, Messier 5, and Messier 15. All of these clusters contain many variables, of which the periods were determined originally by the same observers, namely Bailey and

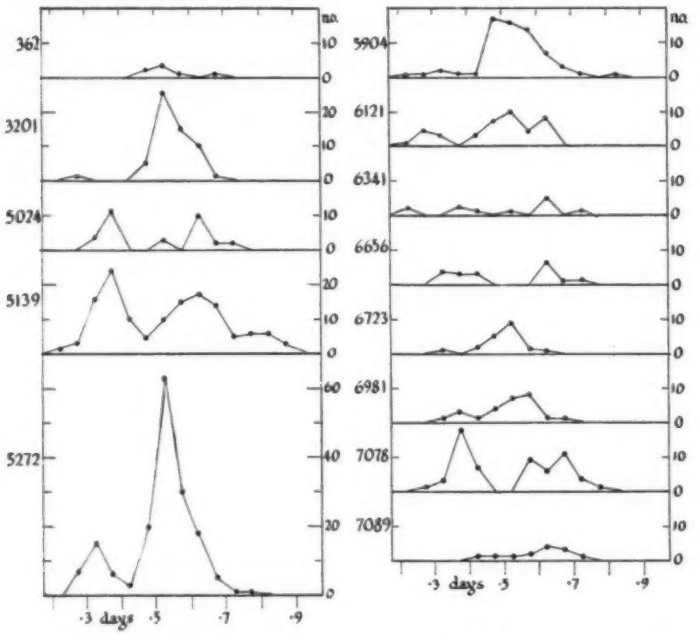

Fig. 1.—Distribution of periods of cluster type variables in thirteen globular clusters. Abscissae, periods grouped to 0.05 day; ordinates, numbers of variables.

his associates, and then later checked by other observers. These curves illustrate the very real difference in distribution which exists from cluster to cluster.

It must be admitted that in some of the clusters there are undoubtedly still undetected cases of erroneous periods which may

give a false distribution. But if the proportion of such cases is not large (and it is not likely to be) the main trend of the curve will not be much affected.

The data of Table I were computed on a percentage basis, that is, the proportion of periods in any group to the total number of known cluster type periods per cluster. The resulting curves are shown in Figure 2.

From an inspection of these two figures, it may be seen that the frequency-distribution follows three different patterns: (1) pronounced singe maximum, type Ia, (2) single maximum with slight secondary, type Ib, (3) pronounced double maximum, type II. Table II lists the individual clusters under the group in which they appear to fall, with the interval of maximum period-frequency tabulated.

TABLE II

Group I*a*		Group I*b*			Group II		
N.G.C.	Single Maximum	N.G.C.	Primary Maximum	Secondary Maximum	N.G.C.	Maximum	Maximum
362	.50 - .55	5272	.50 - .55	.30 - .35	5024	.35 - 40	.60 - .65
3201	.50 - .55	6121	.50 - .55	.25 - .30	5139	.35 - .40	.60 - .65
6341	.50 - .55						
6723	.50 - .55	5904	.45 - .50	.35 - .40	6656	.30 - .35	.60 - .65
7089	.60 - .65	6981	.50 - .55	.35 - .40	7078	.35 - .40	.65 - .70

The usual distribution of periods appears to have a single maximum, or single with slight secondary, as exemplified by the variable-rich clusters NGC 3201, Messier 3, and Messier 5. The double maximum exhibited by such rich clusters as Omega Centauri and Messier 15 is a less common type. The actual gap in time in which no periods have been found is noteworthy, especially in Messier 22 which has the largest gap, amounting to 0.18 day.

It will be noticed that a slight shift in the time scale will make the curves in any group resemble one another. But no shifting in the time scale will make the curves from one group resemble those from another.

From an inspection of the curves, we see that where a single maximum occurs, it generally falls within 0.05 day of half a day. That is

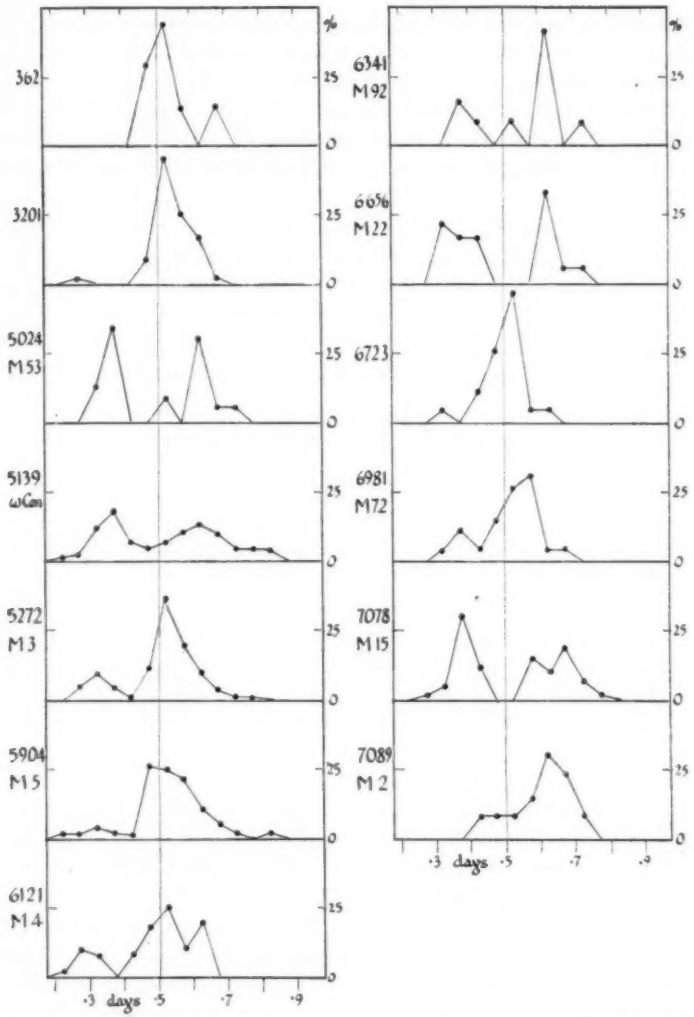

Fig. 2.—Proportion of periods in thirteen globular clusters in 0.05 day intervals. Ordinates, percentage of periods in given interval as compared with all cluster type periods known in a given cluster.

to say, the presence of many variables with periods between 0.45 day and 0.55 day in general appears incompatible with the presence of many other cluster type variables whose period differs by more than 0.05 day from this amount. A logical question, which cannot be answered at present, is whether a secondary maximum might come in with periods below 0.2 day, for those clusters with a single maximum at half a day. Very short periods are difficult of detection in such distant objects.

Of the clusters plotted, the most obvious exception to this single maximum rule is Messier 2. This is a cluster rather thoroughly investigated by the writer at Victoria, but the plates did not include faint enough objects to permit the discovery of variables with half a magnitude range in the 16th magnitude. A recent re-examination of some new plates by the writer leads to a suspicion that there may be a number of small-range cluster type variables undiscovered in the cluster, which would bring in a secondary maximum on the curve, presumably, as indicated by their very small range, at a third of a day.

A correlation of these groups against various properties of the cluster, such as concentration class, galactic position, declination, number of classical Cepheids, etc., has been tried without finding anything of significance, except in the case of integrated spectral class, as listed by Miss Cannon.[9] The clusters of Group Ia are mostly G5; of Group Ib, F or G; and Group II are mostly unclassified, possibly indicating an F spectrum, since an integrated F would be harder to detect. There is not enough evidence here for a spectral correlation, but there is a suggestion that such a correlation might exist.

Summary

1. A frequency curve of the length of period of cluster type variables in 13 globular clusters emphasizes the great difference from cluster to cluster already noted from fewer clusters. It seems to indicate that where a single maximum frequency occurs, it comes at about half a day; where two maxima occur, they fall close to two thirds and one third of a day.

2. The difference of period length from one cluster to the other does not depend upon the cluster's position in the sky (hour angle

difficulties) or upon an individual bias of the observer determining periods. It is a real difference, and must be of considerable significance in the history of globular clusters.

Richmond Hill, Ontario
July 4, 1944.

REFERENCES

[1]Sawyer, *Pub. D.D.O.*, vol. 1, no. 4, 1939.
[2]Bailey, *H.A.*, vol. 38, 1902.
[3]Bailey, *H.A.*, vol. 78, pt. 1, 1913.
[4]Bailey, *H.A.*, vol. 78, pt. 2, 1917.
[5]Bailey, *H.A.*, vol. 78, pt. 3, 1919.
[6]Sawyer, *Pub. D.D.O.*, vol. 1, no. 15, 1944.
[7]Oosterhoff, *Observatory*, vol. 62, pp. 104-109, 1939.
[8]de Sitter, *Natuur. Tijd. voor Ned. Indië*, dl. 101, afl. 2, 1941.
[9]Cannon, *H.B.*, no. 868, 1929.

REVIEW OF PUBLICATIONS

World Wide Planisphere, by Wm. H. Barton, Jr. 10 x 10 ins. Cambridge, Addison-Wesley Press, Inc., 1943. Price $2.50.

This is a rather unique planisphere which can be used in both northern and southern latitudes. Two star maps are given for each hemisphere; one emphasizes the navigational stars, naming them and giving guide lines for ease in identification; the other gives the constellation names and Greek letters. The maps are white stars on a black background. Stars to about fourth magnitude are shown, although no magnitude scale is given. Catch figures of the constellations are dotted in. In the projection used in the maps, the circles of declination are equidistant. Since the maps cover about 160° in declination from the centre to the perimeter great distortion results towards the edges. Even near the equator the distortion is considerable; the stars α, γ, β and κ of Orion appear to form a rough square on this projection instead of the long quadrilateral seen in the sky. No mention of this distortion is given in the text. Distortion is present in all map projections and is the penalty which must be paid when representing a large section of a sphere upon a plane.

Four masks are part of the planisphere; these are for latitudes 20°, 40°, 60° and 80°. Each mask may be folded over any one of the four star maps to give the stars visible at any of these latitudes at any time throughout the year. The stars visible at other latitudes may be obtained by estimation.

Added information is given on the backs of the maps. The first section is on orientation, describing how to find the celestial poles, how to estimate angular distance and a note about the determination of terrestrial latitude and longitude. The angular distances between stars in five star groups are given on drawings. It is to be noted that the position of Albireo in the Northern Cross is in error, although the distance is labelled correctly.

A table gives the constellations in which the five naked-eye planets are to be found from 1943 to 1952. This information has been worked out by the use of the Hayden Planetarium instrument and acts as an

aid in identifying these "wanderers". Tables follow giving the accepted pronunciation of the constellation and star names. The last two pages are extracts from the Nautical and Air Almanacs. The navigational stars are listed giving their brightnesses and positions; mean places for 1943 of additional stars are tabulated.

Wm. H. Barton Jr., who designed the World Wide Planisphere, was the curator of the Hayden Planetarium, New York City, and was well known for his contributions in popularizing astronomy. The planisphere is printed on cardboard and is fairly sturdy. It will be welcomed by those who want to learn the stars from different latitudes.

R. J. N.

Basic Marine Navigation, by Bart J. Bok and Frances W. Wright. 422 pages, 9½ x 7½ ins. Houghton, Mifflin Co., Boston, Mass., 1944. Price $4.50.

Kit of Practice Materials to accompany above text-book, price $1.70.

Professor Bok and Miss Wright of the Harvard Observatory have recently been giving courses on navigation to officers of the Engineer Amphibian Command of the United States Army. This text-book and practice material have been published primarily as an aid in presenting such courses. The experience of the authors in repeatedly teaching this work is evident in the balance and simplicity of this very interesting and serviceable manual.

While the requirements of amphibious units naturally lead to an unusual emphasis on coastwise navigation, *Basic Marine Navigation* includes quite enough material on the rather simpler deep-sea navigation to make this a fairly complete text-book.

Somewhat more than half the book is non-astronomical, dealing with standard subjects such as visual and radio aids to navigation, charts, compasses, piloting and dead-reckoning. Excellent chapters outline the essentials of tides and currents, and of marine meteorology.

The section on celestial navigation very carefully describes the basic principles and instruments used. The various methods of solving the astronomical triangle are outlined. The authors are to be commended for discarding the classical cosine-haversine method of

solving the triangle in favour of modern tabular methods. Direct tabular solutions for altitude and azimuth, as in general use in aerial navigation, can hardly be over-emphasized.

For special circumstances the short tabular methods, derived by dealing with two right angled spherical triangles instead of the initial astronomical triangle, are to be highly recommended. This reviewer, however, regrets the present tendency which requires two or more alternative short-hand methods of solution to be presented in basic text-books. To standardize, in times such as these, on *one* of the short methods, rather than leaving a personal choice, would be of some merit in large-scale training schemes. There is so little to choose between various excellent short methods that to teach and supply the tables for one method throughout the services would be less confusing and more economical. We do not feel it necessary to teach stenographers two systems of shorthand, nor signalmen alternatives to the Morse code.

Bok and Wright present both the Dreisonstock and Ageton methods, but suggest that navigators need learn only one. An appendix gives the complete Ageton table for the short solution.

An interesting chapter on navigation in emergencies shows how a little hand-made equipment can be made to produce respectable results in navigation. In my early youth I was shocked at the story of the failure of the great Samuel Hearne's second exploration of the Canadian north-west (1770) due to an accident to this quadrant. It is important to realize how such accidents can be remedied.

The *Kit of Practice Materials* includes enough charts and computational forms and a small protractor to allow solution of the numerous problems of the text-book in standard form. The text-book includes 150 problems and answers.

Basic Marine Navigation is well printed and attractively illustrated and bound. A post-war edition which further streamlined the section on celestial navigation and expanded the undoubtedly major field of radio navigation, should serve as an excellent peace-time text-book. While the material and treatment are, of course, American rather than British, much of the material is standard.

F. S. H.

Basic Problems in Celestial Navigation, by W. H. Barton Jr. and Charles O. Roth Jr., 56 pp., 6 x 9 ins. Addison-Wesley Press, Inc., Cambridge 42, Mass., 1944. Price $1.00.

Navigator's Work Kit to accompany above text-book, 50 cents.

This booklet, by the late Professor Barton, Curator, and by Mr. Roth, lecturer in navigation, both of the Hayden Planetarium, is fundamentally a series of illustrative worked examples, and of problems with their answers, involving the principles and methods of celestial navigation.

The descriptive matter in each section is very brief, as this volume is designed as a working supplement to navigational text-books, especially the authors' Introduction to Celestial Navigation. Several pages of extracts from the 1943 Nautical Almanac (U.S.) give the astronomical data necessary for the solution of the problems. Of course the solutions also require, in many cases, the various extensive computational tables of the U.S. Hydrographic Office.

The problems range from simple questions on bearings to complete solutions of the astronomical triangle by all the commoner methods. The booklet should be quite useful for instructors and students, though the range of methods is unnecessarily large.

F. S. H.

NOTES AND QUERIES

Communications are invited, especially from amateurs. The Editor will try to secure answers to queries.

The Astronomical Journal

The current issue of *The Astronomical Journal* marks a departure in form, content and auspices of this ancient and notable publication.

"*The Astronomical Journal* was founded in 1849 by Benjamin Apthorp Gould, who edited and supported it until, at the end of the sixth volume, in 1861, its issue was interrupted, first because of the war, afterward by Gould's absence abroad during a period of fifteen years. The publication was resumed in 1885 by Gould, who continued to edit the *Journal* until his death in 1896. Since that time *The Astronomical Journal* has been supported financially in part by the Benjamin Apthorp Gould Fund, administered by the National Academy of Sciences. During the years 1909-1941 it was issued from the Dudley Observatory at Albany, New York; since 1941, when the American Astronomical Society became the owner and publisher, from Yale University Observatory."

In its new form *The Astronomical Journal* will publish abstracts of papers presented at the meetings of the American Astronomical Society, and reports of observatories. These items were previously printed in *Popular Astronomy*, and reprinted for the members by the Society. As well as these it will, as in the past, publish original observations and researches in astrometry, theoretical astronomy and celestial mechanics. The fields of astrophysics and "popular" articles will be left for other publications.

Volume 51, number 1, the current number, contains an excellent symposium on Dwarf Stars and Planet-like Companions; papers on errors in astrometric positions, results of occultation observations, and an ephemeris, for 1944-1945, of the asteroid Eros; abstracts of eleven A.A.S. papers, and the reports of two observatories. The material is excellent, well balanced, and the form of publication is attractive.

With the background of solid contribution to astronomical research which the *Journal* has made during the past century, with capable editing by the Yale astronomers, and the official sponsorship by the American Astronomical Society, *The Astronomical Journal* will have an assured and important future.

Le Cercle Astronomique de Montmagny

We have recently received a little pamphlet, "Cognoscere", from the newly organized Cercle Astronomique de Montmagny. This contains a brief article on the importance of the study of astronomy, an outline of the development and aims of the Montmagny Cercle, and its constitution. The work of the club is being carried on in collaboration with the Quebec Centre of the Royal Astronomical Society of Canada.

Montmagny is a town and county south of the St. Lawrence, and some thirty miles east of Quebec City. We wish this new society of French-Canadian amateur astronomers much pleasure and success in its work.

F. S. H.

The Business of Life

I long ago lost a hound, a bay horse, and a turtle-dove, and am still on their trail. . . . It is true, I never assisted the sun materially in his rising, but, doubt not, it was of the last importance only to be present at it. . . . At other times watching from the observatory of some cliff or tree, to telegraph any new arrival; or waiting at evening on the hill-tops, for the sky to fall, that I might catch something, though I never caught much, and that, manna-wise, would dissolve again in the sun.—Thoreau in "Walden."

C. A. C.

Greetings from Soviet Scientists

The wide organization and notable achievements of scientists in Russia during recent years have called forth many commendatory remarks. Various articles in the magazine *Science* have given lists of scientific problems to which solutions have been secured or on which work is progressing. In other matters also efforts are being made to unite the sympathies of the Allies in the present world conflict. In connection with the latter, a cablegram was received from Moscow at the head office of the Royal Astronomical Society of Canada, which ran as follows:

Royal Astronomical Society of Canada,
198 College St., Toronto.

Third antifascist meeting Soviet scientists will be held Sunday, June 18, 17.30 p.m. Moscow time. Aim meeting is to discuss crimes Fascist invaders against science and work restoration scientific research and cultural institutions liberated areas. Proceedings meeting will be broadcast. Soviet scientists antifascist committee takes opportunity convey greetings scientists your country from Soviet Union. We hope collaboration and solidarity men science will speed victory united nations over German invaders—most vicious enemies mankind and persecutors science and culture.

Signed on behalf Soviet scientists antifascist committee academicians.

N. Derzhavin, P. Kapitsa, Moscow.
Kropotkina.

To this message the following reply was sent by the General Secretary:

Soviet Scientists Antifascist Committee, P. Kapitsa.

Reciprocate kind greetings. Heartily in agreement with your sentiments regarding collaboration of scientists for victory and advance of science and culture.

Royal Astronomical Society of Canada.
E. J. A. Kennedy.

The broadcast was to be on June 18 at 10.30 a.m. E.D.T. Reception from Moscow is difficult in Canada and there was no promise that it would be re-broadcast in English. The present writer would be pleased to learn if the message was received by any listeners in America.

C. A. C.

THE JUNGFRAU AT EVENING

By the Old Monastery's ancient spires
And Interlaken's swiftly-moving stream,
With everlasting hills on every side,
The artist finds fulfilment of his dream.

Beyond the narrow pass through lesser steeps,
The Jungfrau proudly lifts her head on high,
Her radiant brow festooned with cirrus clouds,
Her snowy summit pillowed on the sky.

The hours are hastening to the close of day,
The sombre shades of night on meadows rest;
And over flower-flecked slopes the dimness spreads
As slowly sinks the sun out in the west.

Up, up, from height to height the shadows pass,
Till only snow-capped horns are bathed in light:
The sun withdraws his iridescent beams,
Bidding each peak in turn a fond good-night.

Still one, the Jungfrau, topping all the rest,
In golden light and roseate hue is drest;
And there with grand sublimity she sheds
A touch of heaven's glory from her crest.

The sun, enchanted with the scene portrayed,
In colors that defy the painter's art,
Lingers awhile to give a last caress,
Then dons his purple mantle to depart.

H.W. Barker.

MEETINGS OF THE SOCIETY

AT EDMONTON

January 13, 1944.—The application for membership of Mr. H. R. Milley was approved on motion by Dr. Gowan and Dr. Campbell. Mr. Chambers felt he could come to meetings again, and asked that his membership be renewed.

The HANDBOOK talk was given by Mr. Wates. The occultation of Jupiter by the moon that morning had been observed successfully with his nine-inch telescope. Saturn is in the most favourable position for observation that it can be in thirty years. Everyone should try to see it through a good telescope. Jupiter is becoming prominent again. A solar eclipse occurs in January, but is invisible here.

Dr. Campbell reported his own and Mr. Keeping's experiences in observing the Jupiter occultation. The early clouds cleared just at the right time and there was superb seeing at the critical time of ingress. Other clouds came over but the sky cleared again at egress though the seeing was not quite so good.

The main paper "Astro-Navigation" was given by Flight-Lieutenant Crossley from No. 2 A.O.S. There are four methods of navigation.

(1) By Iron compass or Bradshawing, i.e., following a railroad.
(2) By map reading if the visibility is good.
(3) By intersection of two position lines giving a "fix". This may be visually or by radio, but may not be accurate if the static is bad, or if the radio frequency is jammed by the enemy.
(4) By the stars. This may involve climbing through a cloud layer, which can always be done unless icing conditions are too bad.

In elaborating on the fourth method the meanings of many terms used was made clear, e.g., substellar point, Greenwich hour angle, declination, local hour angle. With the complement of the altitude of some star the radius of a position circle can be found. Repetition with another star gives another circle. The intersection of these two gives a fix, and it is easy to tell which of the two intersections to use. For accuracy a large scale is necessary. This would mean a large globe, which is impractical. Smaller maps cannot include a substellar point. A method of procedure due to Marq St. Hilaire is currently in use to get around the difficulty.

Assume a position, and take the time, and the altitude of a star. Computation with convenient tables makes it possible to draw a position line, which is really a short segment of the large position circle. A corrected parallel line can be drawn using the observed altitude. Repetition of this with another heavenly body gives another corrected line. The intersection gives a position fix. The system of computation gives the result in a few minutes to an accuracy of less than 10 miles. The tables are not refined enough for greater accuracy but the speed is essential. Altitude is taken with the bubble sextant, often under

bumpy conditions, and the latest model averages the reading automatically by clockwork over a time of two minutes.

A tribute was paid to the astronomers whose detailed calculations are essential in preparing the special tables used.

There was no time for discussion, and the meeting adjourned to Room 111 for refreshments at 10 o'clock. There were 41 members and visitors present.

February 10, 1944.—The Librarian reported that Mr. Hamilton had presented a copy of Moulton's "Consider the Heavens" in memory of the late H. A. Plumb, a charter member of the Centre. Also Mr. McLean has presented some books and telescope material. On the motion of Mr. Keeping and Dr. Campbell the secretary was instructed to write letters of appreciation.

A standing tribute to the memory of Mr. E. N. Higinbotham, recently deceased, was paid by the meeting. Mr. Higinbotham was a charter member, and served many years as Treasurer of the Centre. Flowers were sent by the Executive, and an acknowledgement has been received.

The HANDBOOK talk was given by Dr. Campbell. The equation of time gives a maximum correction to the sundial on February 12. From that date the mornings will begin to lengthen faster than the afternoons. An explanation of the principal orbital elements of the Solar System was given with the help of sketches.

Miss Anna Malanchuk gave the main paper on the topic "Mars". Close observation in ancient times gave information about the planets and their periods,—Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn. All were gods in Greek mythology, and gave names to the days of the week. Mars is nearest the earth, and has two moons, one of shorter period than the Martian day. Hence this one rises in the west, and sets in the east as seen from the planet.

The nearest approach is 34.6 million miles, giving good opportunity for observation of detail. Polar caps show seasonal changes. Brick-red parts seem to be deserts, and darker regions are probably some kind of vegetation. Visual observation, when good, gives more detail than photographs. These details change, and there is much disagreement about them.

There are probably no highly developed forms of Life as we know them. Temperature changes are very great, there is little oxygen, and no large bodies of water on Mars.

A lively discussion followed the paper. The markings and their boundaries change considerably. Observations with the new 200-inch telescope will not be much better because of dependence of good seeing through our own atmosphere. Barnard thought a photograph was good if it agreed with what his own eyes saw. Jeans' views on the possibility of life on the other planets was mentioned. Mars' faster moon is one of the reasons why Laplace's Hypothesis has been abandoned.

There were 27 members and visitors present.

E. H. GOWAN, *Honorary Secretary.*

The Royal Astronomical Society of Canada

OFFICERS FOR 1944

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